Dualities in heavy-ion collisions

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JINR

OUTLINE

Dualities = Different descriptions (with different accuracy under the different conditions) of same processes

Quark-hadron

Hydro- kinetic

Statistical-gravitational (geometrical)

Strong interactions and gravity in HIC

$E_{EM}/E_G \sim e^2/(m/M_{Pl})^2$ $M_{Pl} \sim 10^{18}$ GeV

For 2 particles with M_{Pl} mass at Compton wavelength distance $(1/M_{Pl})$: $E_G \sim (G = 1/M_{Pl}^2)\ M_{Pl}^2 / (1/M_{Pl}) = M_{Pl}$ g ~ $(G = 1/M_{Pl}^2)\ M_{Pl} / (1/M_{Pl})^2 = M_{Pl}$

Gravitational interaction is strongly suppressed ~ $(\Lambda/M_{Pl})^2$

Equivalence Principle

I: Acceleration <-> Gravity

HIC: a ~ Λ, a/g ~ $\frac{c^2}{v_\oplus^2} \cdot \frac{R_\oplus}{R_A} \sim 10^{30}$

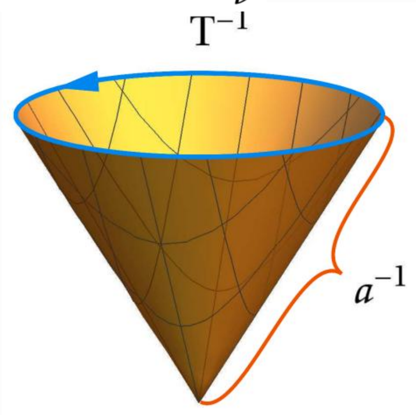
$M_{Pl} \to \Lambda$ ("GeV Gravity")

Emergent conical geometry

[G. Y. Prokhorov, O. V. Teryaev, and V. I. Zakharov. JHEP, 03:137, 2020]

- The effects of acceleration can also be investigated from the point of view of an **accelerated observer**. In this case, the euclidean **Rindler coordinates** are to be used:

$$ds^2 = \boxed{\rho^2 d\theta^2 + d\rho^2} + d\mathbf{x}_\perp^2 \Longrightarrow \mathcal{M} = \mathbb{R}^2 \otimes \mathcal{C}_\nu^2$$



<u>**Dictionary**</u> for translation
thermodynamic characteristics in ***geometrical***:
Inverse **acceleration** ⟺ **distance** from the **vertex**
Inverse proper **temperature** ⟺ **circumference**

- **Two approaches** to calculate acceleration effects:
  1) **Geometrical** (Rindler, conical):
  2) **Statistical** (interaction with **boost**):

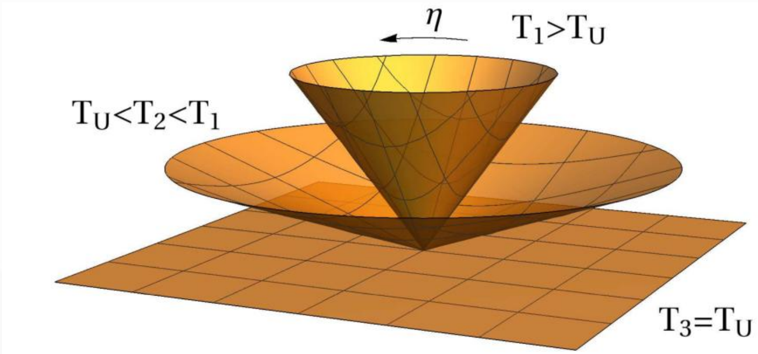
$$\alpha^\rho \hat{K}_\rho$$

$$\rho_{s=1/2} = \frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}$$

Same results - **duality** of two approaches!

- **Novel phase transition** at the **Unruh** temperature in both approaches!

[G. Y. Prokhorov, O. V. Teryaev, and V. I. Zakharov. arXiv:2304.13151. (2023) and work in preparation]



Gravity trace in flat spacetime: Cheshire cat grin

“Well! I've often seen a cat without a grin,' thought Alice 'but a grin without a cat! It's the most curious thing i ever saw in my life!”

— Lewis Carroll, Alice in Wonderland

Flat space limit:
Kinematical Vortical Effect (KVE)

Cheshire cat grin

- Let's move on to the limit of **flat space-time**. Despite the absence of a gravitational field, there **remains a contribution** to the axial current induced by the gravitational chiral anomaly:

Flat: $j_\mu^A = \lambda_1(\omega_\nu\omega^\nu)\omega_\mu + \lambda_2(a_\nu a^\nu)w_\mu$

Curved: $\nabla_\mu j_A^\mu = \mathcal{N}\epsilon^{\mu\nu\alpha\beta}R_{\mu\nu\lambda\rho}R_{\alpha\beta}{}^{\lambda\rho}$

$$\frac{\lambda_1 - \lambda_2}{32} = \mathcal{N}$$

Direct check:

1) Spin **1/2** :

$$\left(-\frac{1}{24\pi^2} + \frac{1}{8\pi^2}\right)\Big/32 = \frac{1}{384\pi^2}$$

2) Spin **3/2** (*Rarita-Schwinger-Adler model*):

$$\left(-\frac{53}{24\pi^2} + \frac{5}{8\pi^2}\right)\Big/32 = -\frac{19}{384\pi^2}$$

- A **new** type of anomalous transport – the **Kinematical Vortical Effect (KVE)**.
- New global polarization (talk of N. Tsegelnik) source?

[G. Yu. Prokhorov, O. V. Teryaev, and V. I. Zakharov, Phys. Rev. Lett. 129, 151601, (2022)]

CONCLUSIONS-I

Duality between statistical and geometric descriptions

Different mechanisms of information loss?

Phase transition in HIC: hadronization ~ fall into Black hole?

Gravitational anomaly: KVE ~ Cheshire Cat grin?

Yet another duality: superstrong (~ m_π^2)magnetic fields vs vorticity

Vector K* mesons in strong magnetic field from SU(3) lattice gauge theory

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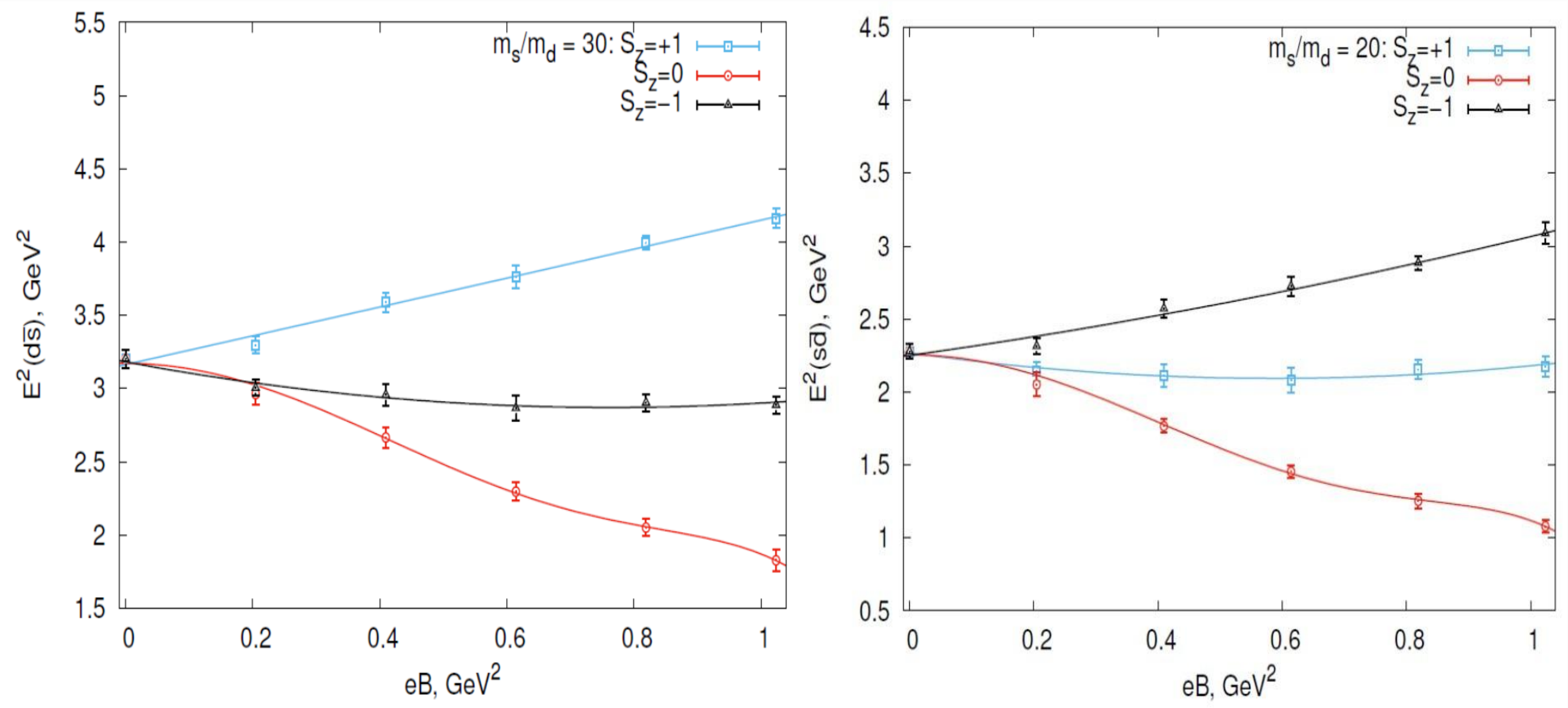
KI ITEP

Introduction

- For the vector K^{0*} and $K^{\pm *}$ mesons we explore on the lattice
  - The dependence of the energy and magnetic properties from spin projection
  - The dependence of the magnetic characteristics from $\frac{m_s}{m_d}$ ratio
- For the K^{0*} and $\overline{K}^{*0}$ mesons we calculate
  - Magnetic moment which is the new effect
  - The magnetic dipole polarizability
  - The tensor polarizability which is the measure of lepton asymmetry
- For the charged vector $K^{\pm *}$ mesons we find
  - The magnetic moment

Energy of vector K^{*0} and $\bar{K}^{*0}$ mesons

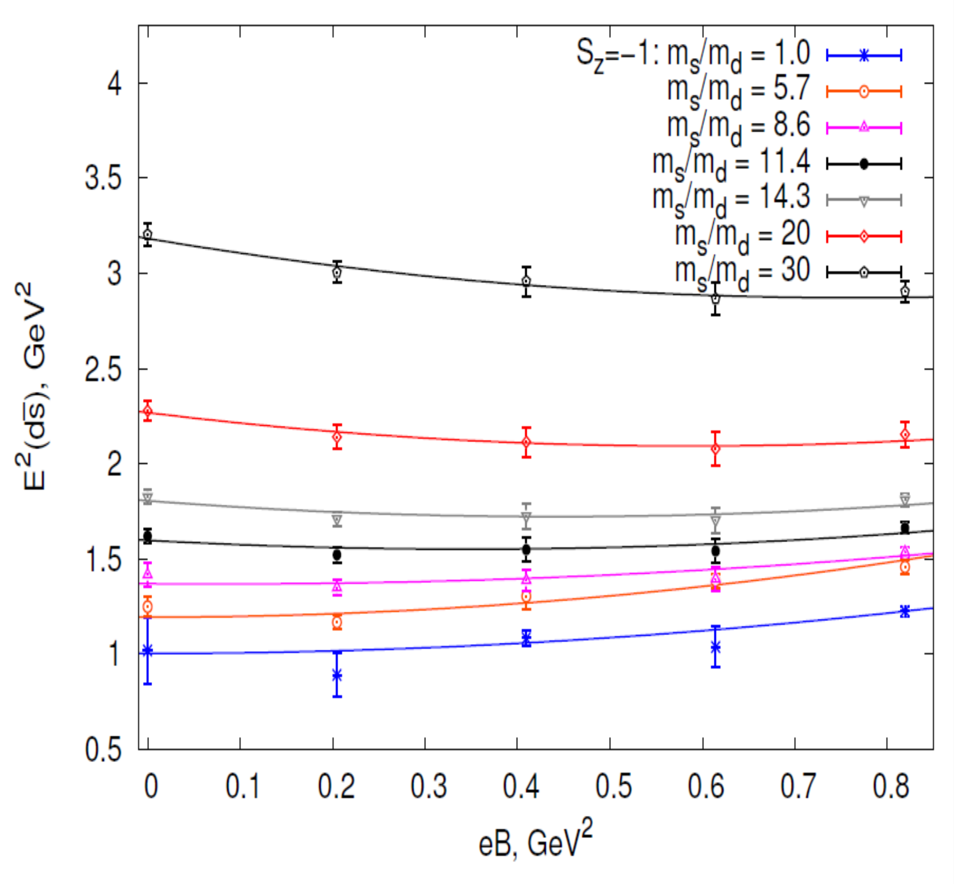


- Lattice parameters: $N_S^3 \times N_t = 18^4$, $a = 0.105\ fm$, $m_\pi = 367(8)\ MeV$

The lattice data are fitted by equations:

- $E^2(S_Z = 0) = m^2 - 4\pi m\beta_m(eB)^2 - 4\pi m\beta_m^{h1}(eB)^4 - 4\pi m\beta_m^{h2}(eB)^6$ at $eB \in [0{:}1.03]GeV^2$
- $E^2(S_Z = \pm 1) = m^2 \mp g(eB) - 4\pi m\beta_m(eB)^2$ at $eB \in [0{:}1.23]GeV^2$

Fits for magnetic moment and polarizability



- The best fit for $\frac{m_s}{m_d} \leq 5.7$:

$$E^2 = m^2 - 4\pi m \beta_m (eB)^2$$

- The best fit for $\frac{m_s}{m_d} > 5.7$:

$$E^2 = m^2 - g(eB) - 4\pi m \beta_m (eB)^2$$

Magnetic moment and dipole polarizability of the K^{*0}meson for spin $S_z = -1$.

Previous results:

- Lattice calculations: $g(K^{*0}) = -0.26$, Hedditch et. al. Phys.Rev.D75 094504 (2007).
- Light cone QCD sum rules $g(K^{*0}) = 0.26 \pm 0.4$,

  Aliev et.al., Phys.Lett B678 470 (2009).
- Field cumulant method $g(K^{*0}) = -0.183$,

  M. Badalian and Yu. A. Simonov, Phys. Rev. D 87 074012 (2013).

Our lattice results:

m_s/m_u	g-factor	$\beta_m(\text{GeV}^{-3})$	p-value	$eB(\text{GeV}^2)$
1	-	-0.026 ± 0.006	0.522	$[0:0.82]$
5.7	-	-0.033 ± 0.003	0.384	$[0:1.03]$
8.6	-0.044 ± 0.106	-0.019 ± 0.005	0.728	$[0:1.23]$
11.4	-0.265 ± 0.100	-0.024 ± 0.005	0.642	$[0:1.23]$
14.3	-0.378 ± 0.097	-0.025 ± 0.004	0.710	$[0:1.23]$
20	-0.599 ± 0.076	-0.027 ± 0.003	0.966	$[0:1.23]$
30	-0.816 ± 0.103	-0.024 ± 0.003	0.913	$[0:1.23]$

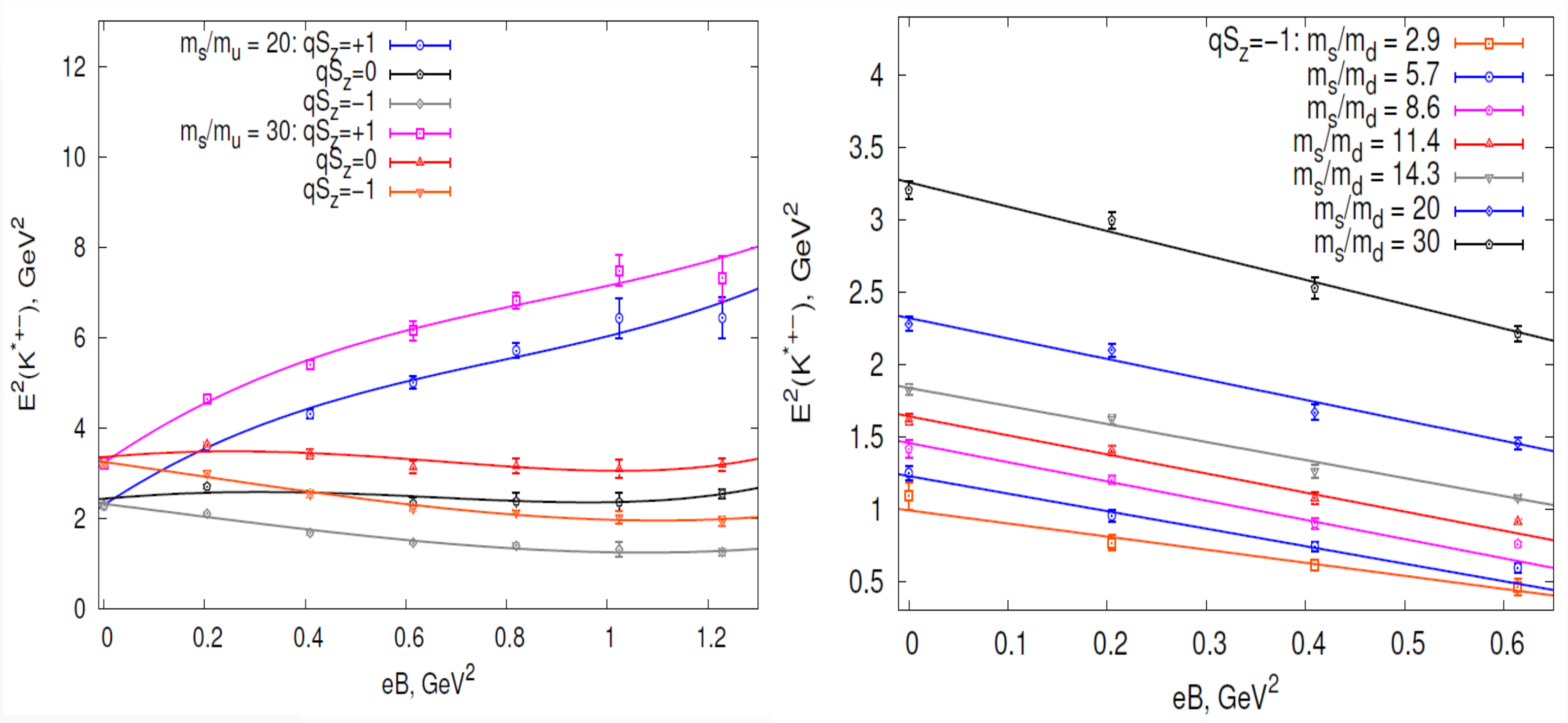
Lepton asymmetry and tensor polarizability for K^{*0} and $\overline{K}^{*0}$ mesons

m_s/m_u	$\beta_{S=+1}(\mathrm{GeV}^{-3})$	$\beta_{S=-1}(\mathrm{GeV}^{-3})$	$\beta_{S=0}(\mathrm{GeV}^{-3})$	β_t
1	-0.026 ± 0.006	-0.026 ± 0.006	0.185 ± 0.022	-3.2 ± 0.3
5.7	-0.039 ± 0.006	-0.033 ± 0.003	0.232 ± 0.044	-3.4 ± 0.4
8.6	-0.018 ± 0.012	-0.019 ± 0.005	0.212 ± 0.019	-3.6 ± 0.3
11.4	-0.019 ± 0.010	-0.024 ± 0.005	0.230 ± 0.039	-3.7 ± 0.3
14.3	-0.016 ± 0.009	-0.025 ± 0.004	0.206 ± 0.019	-2.8 ± 0.2
20	-0.011 ± 0.009	-0.027 ± 0.003	0.187 ± 0.017	-2.8 ± 0.3
30	-0.0002 ± 0.007	-0.024 ± 0.003	0.167 ± 0.019	-2.5 ± 0.2

- The large negative values of β_t indicate that the longitudinal polarization dominates for the decays of these mesons.
- The dileptons are mainly emitted in the directions close to the perpendicular ones to the magnetic field axis.

$$\beta_t = \frac{\beta_{S_z=+1} + \beta_{S_z=-1} - 2\beta_{S_z=0}}{\beta_{S_z=+1} + \beta_{S_z=-1} + \beta_{S_z=0}}.$$

Energy of the vector $K^{\pm *}$ mesons



- We find the g-factor from the fit (right figure)

$$E^2 = m^2 + eB - gqS_z(eB)$$

where q is the meson charge, e is the electron charge.

Magnetic moment of $K^{\pm *}$ mesons

Previous results:

- Lattice background field method from 2pt correlation functions: $|g(K^{\pm *})| = 2.36$,

  F.X.Lee et.al., Phys. Rev. D78 094502 (2008).

- Lattice calculations from 3pt corr. functions: $|g(K^{\pm *})| = 2.23$,

  Hedditch et. al. Phys.Rev.D75 094504 (2007).

- Field cumulant method $|g(K^{\pm *})| = 2.194$,

  M. Badalian and Yu. A. Simonov, Phys. Rev. D 87 074012 (2013).

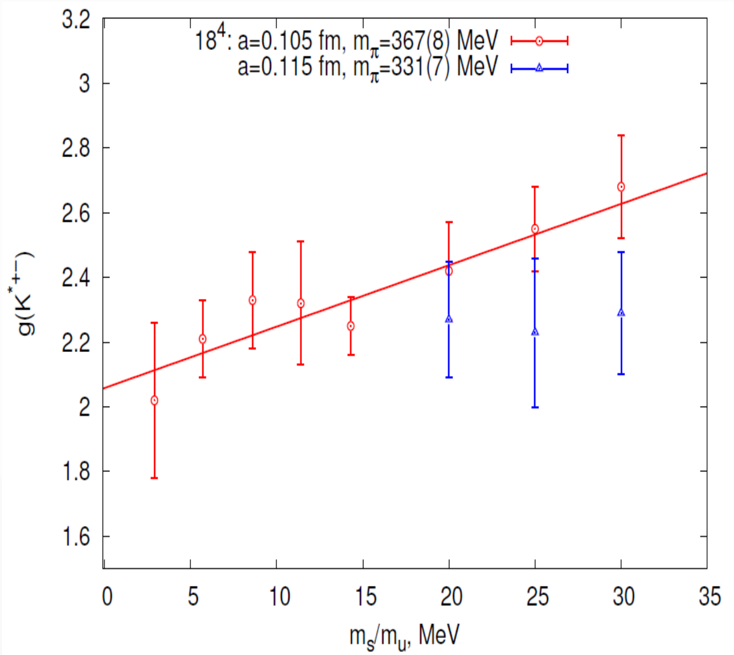
Our lattice results:

for $\frac{m_s}{m_d} = 20$ at $eB \in [0:0.62]\ GeV^2$

$$|g(K^{\pm *})| = 2.42 \pm 0.15.$$

for $\frac{m_s}{m_d} = 30$ at $eB \in [0:0.62]\ GeV^2$

$$|g(K^{\pm *})| = 2.68 \pm 0.16.$$



Conclusions-II: magnetic moment but no tachyonic mode due to strangeness

For K^{*0} mesons

- The g-factor was found
  - The magnetic moment of the K^{*0} meson is negative in value, that agrees with other lattice results.
  - The extrapolations to physical pion mass and continuous limit are necessary.

- The magnetic dipole polarizability was found
- The tensor polarizability is negative in value
  - So the dileptons are mainly emitted in the directions close to the perpendicular ones to the magnetic field axis.

For $K^{\pm *}$ mesons

- The g-factor was calculated